Demonstration of All-Optical Multi-Wavelength Message Routing for Silicon Photonic Networks

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Abstract: We demonstrate all-optical switching of 20 wavelength channels simultaneously in a silicon broadband comb switch, and perform single-channel BER measurements through both ports. A statistical characterization of the insertion loss and extinction ratio is included.

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1. Introduction

With recent noteworthy advances in nanoscale fabrication and dense integration, silicon photonic device technologies have emerged as a viable solution in a multitude of short-reach applications currently dominated by electronic interconnects. Optical technologies supporting the immense bandwidth allocated by wavelength division multiplexing (WDM) and offering low-power switching capabilities may alleviate bandwidth and power limitations in existing chip-to-chip and future on-chip networks [1]. The silicon-on-insulator (SOI) platform is an attractive material system for realizing these photonic integrated circuit (PIC)-based interconnection networks due to its high index contrast and compatibility with CMOS integration [2–4]. Microring resonators present viable building blocks for these systems and have already been shown to perform passive filtering operations, in addition to electro-optic and all-optical switching and modulation [2–4], all within the context of the SOI platform. However, despite much progress in silicon photonic technologies, a low-power, high-speed, compact switch capable of operating over a large spectral bandwidth has not yet been demonstrated. Such a device represents a key building-block functionality for routing WDM data in optical interconnection networks.

2. Broadband Comb Switch

The device structure discussed here, previously reported in [3,4], comprises a ring resonator coupled to two parallel waveguides with widths of 450 nm and heights of 250 nm (Fig. 2). When no pump is applied, input light on resonance with the ring is coupled to the drop port of the device, and light that is off resonance propagates to the through port. The wavelengths of the ring's resonant modes may all be blue-shifted simultaneously by injecting electronic carriers into the device through the free-carrier plasma dispersion effect. As a result, when the wavelength of an optical data signal is aligned on resonance, the presence of a carrier-generating pump source switches the signal from the drop port to the through port. Likewise, the removal of the carriers directs the signal back to the drop port. Carriers may be injected using an optical pump [3] or an electrical signal applied across a *p-n* junction surrounding the waveguide [2].

In the work presented here we switch a multi-wavelength packet cohesively by leveraging the device's small free-spectral range (FSR) of 0.8 nm, allowing many resonator modes to each switch one channel of a WDM signal simultaneously. Moreover, the energy required to switch many channels is the same as that required to switch a single channel. Utilizing the additional resonator modes of the microring, therefore, enables the switching of additional signal bandwidth without significant penalty, aside from its larger footprint (200-μm diameter) compared to microrings with smaller diameter and larger FSR.

All-optical switching of two continuous-wave (cw) wavelengths has been previously demonstrated [3]. Additionally, a 160-Gb/s data stream (16 wavelength channels at 10 Gb/s each) was passed through the switch passively (with no applied pump), and the bit-error-rate (BER) degradation due to inter-channel crosstalk within the ring was found to be negligible when scaling from one to 16 wavelength channels [4]. Here, we demonstrate for the first time full switching of 20 wavelengths simultaneously. We further characterize the passive insertion losses and extinction ratios of the switch along both ports and investigate the BER performance of the all-optically switched data.

3. Loss Characteristics

The transmission spectra of both output ports of the switch, along with a third port (a reference waveguide which has the same length and cross-section as the through-port waveguide), are plotted relative to one another in Fig. 1. On the drop port, the maximum, minimum, average, and standard deviation of the extinction ratios, measured over the 47 resonances shown in Fig. 1, are 18.7 dB, 14.5 dB, 16.7 dB, and 1.2 dB, respectively. On the through port, these values are 28.6 dB, 16.9 dB, 23.0 dB, and 3.2 dB, respectively. The same statistical parameters for the drop port insertion loss, calculated as the difference between the reference waveguide power and the peak drop port power of a resonator mode, are 2.4 dB, 0.6 dB, 1.4 dB, and 0.5 dB, respectively. The measured power from the through port is comparable to that of the reference waveguide, indicating negligible through port insertion loss beyond the waveguide propagation loss.

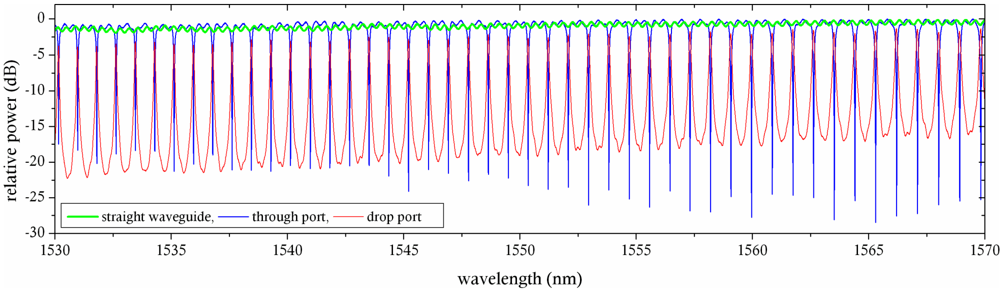

Fig. 1. Relative transmission of through port (blue), drop port (red), and output port of the reference waveguide (green), which is used to evaluate the through port insertion loss (see Fig. 2 for output port definitions).

4. All-Optically Switched Data Signals

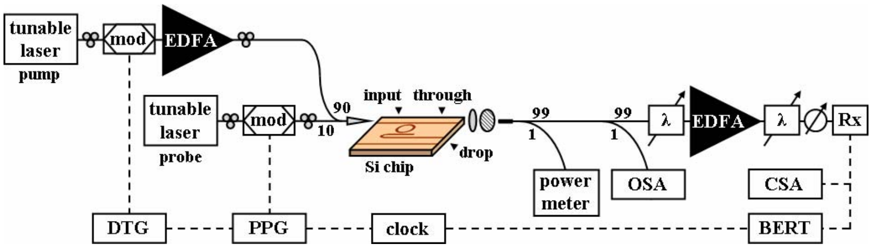

Fig. 2. Diagram of the experimental setup used for BER measurements.

The experimental setup for BER measurements (Fig. 2) consists of two tunable laser sources. The probe is externally modulated with a 10-Gb/s NRZ-OOK signal, encoded using a PRBS of length 2^{31}-1, generated by a pulse pattern generator (PPG). The pump, operating near the wavelength of 1550 nm and generating free carriers through two-photon absorption, is externally modulated using a data timing generator (DTG), which is synchronized to the PPG. Leaving the modulator, the pump signal is amplified using an erbium-doped fiber amplifier (EDFA), and combined with the probe. The signals are coupled into the nanotapered waveguide from a tapered fiber. After exiting the chip, the signals pass through a polarizer, selecting the TM-like polarizations, and are collimated and collected into a fiber. The probe then propagates through a tunable grating filter (λ), an EDFA, another tunable grating filter, and a variable attenuator, and is received by a high-speed receiver (Rx) with a transimpedance amplifier/limiting amplifier pair. The probe signal is analyzed with a communications signal analyzer (CSA) and a BER tester (BERT) that is synchronized to the PPG through a 10-GHz clock. A fraction of the pump and probe power is tapped-off before the first filter for examining on an optical spectrum analyzer (OSA) and a power meter.

The BER measurements are taken by maximizing the output coupling for the drop port of the switch and aligning the probe's wavelength such that it exits from the drop port when the pump is disabled. The pump, composed of 12.8-ns square pulses repeating every 102.4 ns, is aligned in wavelength to a different resonator mode, causing all modes to shift when the pump is enabled. The switching ratio and the transition times of the probe after exiting the drop port (Fig. 3b) may be improved with a more optimal pump configuration, and the transition times can be further reduced to less than 100 ps by applying the techniques described in [2]. The BERT is gated to take measurements only during the arrival of data exiting the drop port (pump OFF). While a single channel is actively switched through the device, error-free operation (BER of less than 10^{-12}) is first verified; BER measurements are then performed (Fig. 3a). Next, the output coupling is maximized for the through port of the switch, using the same pump and probe signals. The BERT is now gated to take measurements only during the arrival of the data exiting the through port (pump ON). Again, error-free operation is verified, and a BER curve is recorded (Fig. 3a). Finally, the back-to-back BER curve is taken by coupling into the reference waveguide with no applied pump (Fig. 3a).

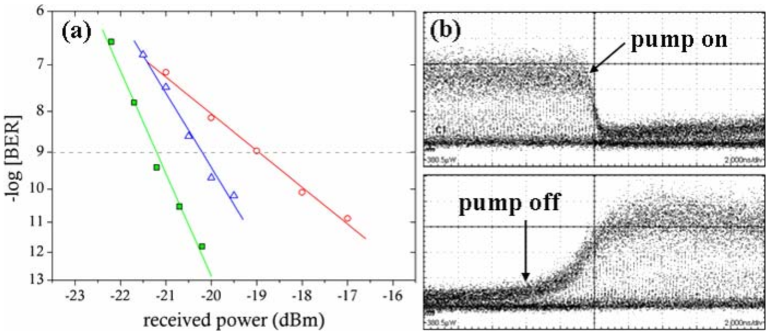

Fig. 3. (a) BER curves recorded for a signal exiting the through (blue, △) and drop (red, ○) ports while the switch is active, and back-to-back measurements through a waveguide with no pump signal present (green, ■). Power penalties of 1 dB (through port) and 2.3 dB (drop port) are observed. (b) Scope traces of switched optical data egressing from the drop port illustrating the switching ratio and transition times with time scales of 2 ns/div.

5. Multi-wavelength Switching

Finally, multi-wavelength switching (Fig. 4) is demonstrated by simultaneously passing 20 WDM channels through the drop port in the presence of the pump signal. The wavelengths span 25 nm, comprising channels C21–C27, C33–C38, and C46–C52 of the ITU C-Band grid. The switching extinction ratios are somewhat degraded by the EDFA noise, but even afterwards range from 4.5 dB to 7.0 dB with an average value of 5.6 dB.

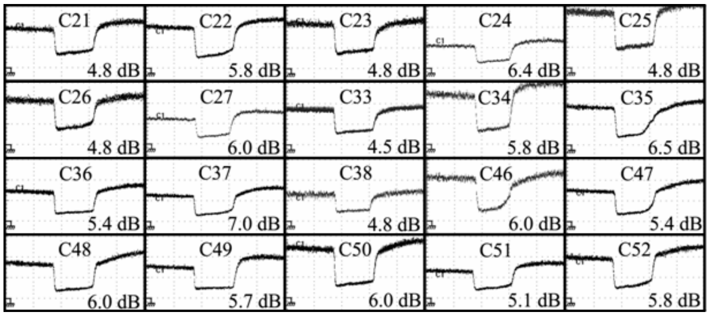

Fig. 4. Waveforms exiting the drop port of the device under active operation, with corresponding labels of the ITU channel and extinction ratio using a 32-point average and 10-ns/div time scale. No limiting amplifier is used.

6. Conclusions

We demonstrate, for the first time, all-optical switching of 20 wavelengths spanning 25 nm simultaneously in a silicon photonic switch. Power penalties of 1 dB and 2.3 dB are measured at the through and drop ports, respectively, under active operation at near-GHz speeds. Based on previous evidence suggesting negligible BER degradation from wavelength-channel scaling [4], the demonstrated low-penalty active operation, and the broadband loss uniformity we report here, the device can be envisioned to function as a viable high-speed broadband switch for integrated silicon photonics used in chip-to-chip and intra-chip networks.

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7. References

[1] A. Shacham, B. G. Lee, A. Biberman, K. Bergman, L. P. Carloni, "Photonic NoC for DMA communications in chip multiprocessors," in Proc. 15th Annu. IEEE Symposium High-Performance Interconnects (HOTI 2007), Stanford University, CA, Aug 2007.

[2] Q. Xu, S. Manipatruni, B. Schmidt, J. Shakya, M. Lipson, "12.5 Gbit/s carrier-injection-based silicon micro-ring silicon modulators," Optics Express, vol. 15, no. 2, pp. 430-436, Jan 2007.

[3] P. Dong, S. Preble, M. Lipson, "All-optical compact silicon comb switch," Optics Express, vol. 15, no. 15, pp. 9600-9605, Jul 2007.

[4] A. Biberman, P. Dong, B. G. Lee, J. D. Foster, M. Lipson, K. Bergman, "Silicon microring resonator-based broadband comb switch for wavelength-parallel message routing," in Proc. 20th Annu. Meeting IEEE Lasers and Electro-Optics Society (LEOS 2007), Lake Buena Vista, FL, paper WG3, Oct 2007.